LCA Methodology

Allocation in Recycling Systems

An Integrated Model for the Analyses of Environmental Impact and Market Value

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Abstract. 'Design for Recycling' and dematerialization by enhancing the durability of products are major aspects of the quest for sustainable products. This article presents an LCA-based model for the integrated analyses of the product chain, its recycling systems, and its waste treatment systems at the 'End of Life' stage. The model is an extension of the EVR (Eco-costs/Value Ratio) model which has been published in this journal (Vogtländer et al. 2001), but can also be applied to other life cycle interpretation models, since the model as such is not restricted to the use of the eco-costs as a single indicator.

The model has been developed to evaluate the design alternatives of complex products like buildings and cars. These products comprise several subsystems, each with its own special solution at the End of Life stage: Extending of the product life, object renovation, re-use of components, re-use of materials, useful application of waste materials, immobilization with and without useful applications, incineration with and without energy recovery, land fill.

Since complex product systems always comprise a combination of these design alternatives, a methodology is given to calculate and allocate the eco-costs of the total system in order to select the best solution for sustainability. The methodology is characterized by:

- A main allocation model of the recycling flow based on physical relationships,
- a strict separation of the market value, the costs and the eco-costs in the system,
- a main allocation model for extension of lifetime based on 'depreciation of eco-costs', parallel to economic depreciation.

Keywords: Allocation; eco-costs; eco-efficiency; end of life; EVR; environmental impact; LCA; recycling; renovation; product-service systems; single indicator; sustainability; waste materials

1 Introduction: Current issues with regard to the End of Life stage of products

1.1 Complexity

The End of Life stage of products is a rather complex stage. Products are collected and dismantled, materials are separated and upgraded, waste is incinerated or dumped, toxic materials are immobilized or incinerated. In terms of the LCA, it is a problem that materials of products are combined with materials of other products, which causes fundamental problems with regard to allocation (Klöpffer 1996, Ekvall 1997).

The economics in the End of Life stage is rather complex as well, since *products* and *materials* in the End of Life stage often have a negative market value (price) as such. The *activities* to recycle these products and materials in an environmentally correct manner, however, have a positive added value for our society as a whole. This results in a situation where the 'free market' has to be restricted in many ways by governmental regulations (e.g. prohibition of dumping certain materials and/or products in land fills), and where the government has to force industry to recycle their products in a correct manner.

In terms of the EVR model (see the Appendix for a short description of the model), the aforementioned complexity means that:

- The allocation model of the End of Life stage must be defined in an unambiguous way, and
- the 'value' of components and materials in the End of Life stage must be determined (value is defined here as the market value or market price)

1.2 Three common ways of looking at the End of Life (EoL) of products

To unravel the complexity, we may distinguish 3 common ways of looking at the EoL (the 3 EoL paradigms):

- The cycle,
- the chain,
- the cascade.

'The cycle' is depicted in Fig. 1, being the idealists way of 'how it should be': when 100% of the products and/or materials are recycled, all problems of materials depletion and land fill are resolved.

Modelling the End of Life as one single recycle loop, however, one must cope with two important aspects of the reality:

1. 'The second law of thermodynamics', requiring an 'upgrading' activity and requiring 'bleed flows' to cope with degradation, contamination and dilution of materials within the loop,

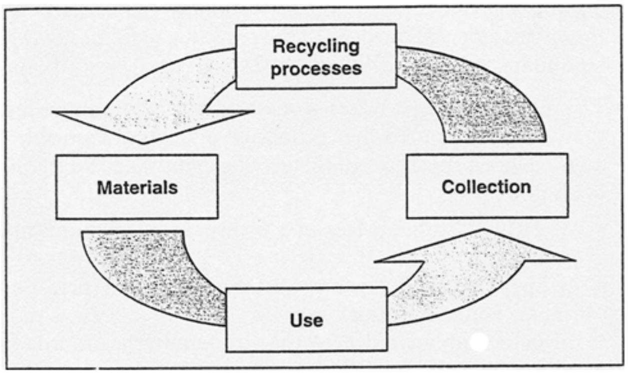

Fig. 1: The End of Life system from the point of view of idealists: 'The cycle'

2. 'the many lives of recycled materials', i.e. materials do not stay in one product loop, but switch to other product loops ('cascading' down to other life cycles).

'The chain' is depicted in Fig. 2, being the way product designers and engineers approach the problem of EoL. The recycling systems as such (after the separation step) are normally not included in the product analyses. 'The chain' is the way EoL is configured in design tools like Simapro, Ecoscan and in the EPS system.

The main focus within this paradigm is twofold:

A. Try to apply recycled materials for construction elements of the new product or structure, and
B. make it technically feasible (easy) to disassemble or dismantle the product or structure: 'Design for recycling' (the 'separation' step in Fig. 2).

Depicting End of Life as 'a chain' doesn't cope with two important aspects:

1. The recycling activities as such cannot be analysed (alternative systems for transport and upgrading after the separation step), since recycling systems normally combine many 'chains',
2. the sense or nonsense of recycling activities as such, with regard to the general subject of sustainability, cannot be analysed (questions like: Is it wiser to recycle a certain type of plastic, or burn it?).

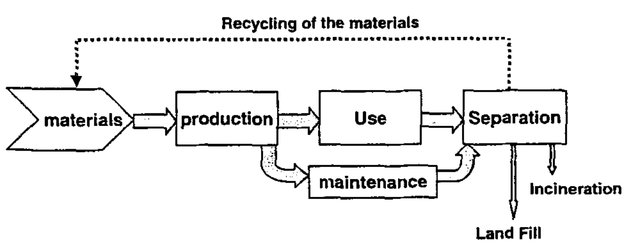

Fig. 2: The End of Life system from the point of view of product designers: 'The chain'

'The cascade' is depicted in Fig. 3, being the way most of the business managers as well as LCA-specialists approach the problem of End of Life. The main focus within this paradigm is "can we do something useful with the old product, or, do we have a 'second life' for the old materials". In the strict sense, 'the cascade' is not a form of recycling, but rather a form of re-use of the degraded materials themselves (examples are waste paper, fly-ash, crushed stones and crushed concrete).

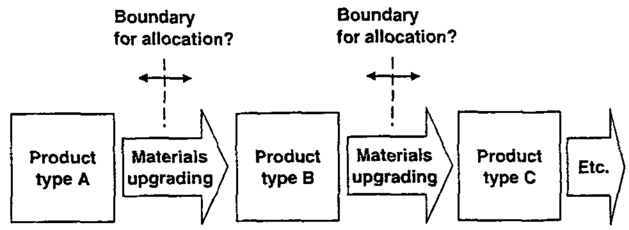

Fig. 3: The End of Life system from the point of view of LCA experts: 'The cascade'

The cascade is regarded as the fundamental way to optimize the use of resources (Sirkin et al. 1994).

The cascade has triggered many proposals and debates among LCA-specialists on the subject of allocation:

1. Must the environmental burden related to use of virgin materials be allocated to the first product only, or must this environmental burden partly be allocated to the second and third use for products as well? (In The Netherlands, this allocation to a second and/or third product life is called the 'estafette method', referring to relay races).
2. Given the fact that the End of Life activities (like separation, transport and upgrading) are causing environmental burden, which of these activities must be allocated to which product?

1.3 Order of Preferences of EoL solutions in The Netherlands ('Ladder of Lansink')

Given the complexity of the EoL systems, the government of The Netherlands adopted an order of preferences of EoL solutions on which to base the governmental policy. This is a sort list of five EoL solutions, the so called 'Ladder of Lansink':

1. Re-use of the product (example re-usable crates for transport of consumables),
2. re-use of the materials of a product (example recycling of glass and metals),
3. incineration with energy recovery,
4. incineration without energy recovery,
5. land fill.

This order of preferences for policy making of the Dutch government was implemented in 1979, and is still the basis for decisions on regulations, legislation, taxation and subsidies.

Designers of a so called Product-Service System (PPS) think along the same lines:

a. Try to bring the recycling activity within the PPS and 'close the loop' (create 'the cycle'),
b. when a. is not a practical solution, create 'the chain' with maximum materials recovery,
c. when b. is not feasible (because of severe degradation), try to create 'the cascade' + incineration with energy recovery.
d. Incineration without energy recovery and landfill must be avoided.

Although the list of preferences has its basic logic, and although it has served successfully as a catalyst for Dutch policy making for two decades, the need for a better system is felt under a vast majority of the people involved:

- There is a need for a more refined list of preferences,
- there is a need for a calculation model to check which of the EoL systems on the list is the best practical solution for a specific case in terms of sustainability[1].

In Chapter 3 such a new refined list of preferences is proposed, and it is shown how to make calculations on the eco-costs and the EVR in the chapters thereafter.

First, an overview of the existing theories on allocation in cascade systems will be provided in the next chapter.

2 Existing Theories for Allocation in Cascade Systems

As mentioned in Chapter 1.3, the main debate on allocation of EoL activities concentrates on 'the cascade' of Fig. 3. The main question is where to allocate the environmental burden related to the primary production of materials, the recycling activities, and the final waste treatment.

The classical approach of LCA practitioners of separating the assessment of the product chain and the assessment of the recycling system is inappropriate: innovative designs of product-service systems require an integrated assessment of both the product chain and its recycling systems. This becomes even more relevant in cascade systems.

The ISO 14041 norm provides a framework on how allocation problems should be tackled. It describes a three-step procedure with regard to allocation[2].

As a first step, allocation should be avoided where possible (by dividing the process into subprocesses or by expanding the product system). As a second step, when allocation cannot be avoided, allocation must be done in a way which reflects an underlying, causal, physical relationship. The third step is about 'other relationships' such as market value.

Some authors argue that economic allocation cannot be avoided here, since neither of the two first steps are feasible, and since the boundary line in Fig. 3 always leads to arbitrary choices (Lindfors 1995, Lindeijer et al. 2000, Werner et al. 2000, Ekvall 2000). The question is, however, whether economic allocation, based on the – heavy fluctuating – market prices of recycled materials, will lead to better results than the simple methods which were originally proposed, such as: "shifting the secondary materials outside the system boundaries" (Klöpffer 1996), or the 'simple cut-off method', where a product made out of primary materials carries the environmental burdens of those primary materials and a product made out of secondary materials carries the environmental burdens of the recycling activities of those secondary materials (Ekvall 1997).

The EVR model provides a method for economic allocation, but it is argued that economic allocation can only be applied when specific criteria have been fulfilled (Vogtländer et al. 2001):

- Relatively stable prices in a transparent, free, and open market,
- a linear relationship between market value (price) and mass, volume and/or time.

It must be emphasised here that these criteria are *not* fulfilled for the economic allocation models, which have been proposed recently, since:

- Prices for products like scrap and waste paper are highly volatile (unstable),
- the markets for these waste materials are highly influenced by governmental policies, and
- there is no simple, linear, relationship between market value (price) and mass.

The economic allocation model which has been proposed by CML (Lindeijer et al. 2000) is taken here as an example of a recent economic allocation model, since it shows quite clearly that the boundaries for allocation shift with the market price of the waste materials. In this model, the EoL activities are being allocated to the next product when the next product pays for the waste (that is when the waste material has a positive market value).The model is depicted by the example on "a house to be demolished and processed into road building material" (**Fig. 4**).

In Fig. 4, the environmental burden of the activities in the grey blocks is allocated to the road, the environmental burden of the other activities is allocated to the house. In Fig. 4, four situations have been depicted. Quoted from (Lindeijer et al. 1999): " ...

- Variant A: Waste flow value positive from building, and hence even more positive after processing and in road structure,
- Variant B: Waste flow value zero from building, value positive after processing and in road structure,

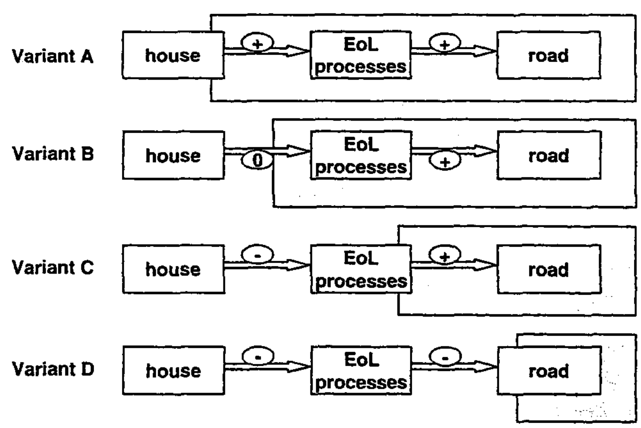

Fig. 4: The CML allocation model for the situation where materials of a house after demolition are used in road construction, from (Lindeijer et al. 1999), simplified

[1] Note that, for a specific case, the sequence of preferences of the best practical solutions in terms of sustainability can deviate from the general sequence. An example is the best choice of transport packaging for medium distances, where re-use of the product (the re-usable crate system) is less favourable than re-use of material (the board from recycled paper system) because of the extra return transport of the empty crates.

[2] Allocation is defined in this ISO as: Partitioning the input and/or output flows of a process to the product system under study. For an extensive analysis on the subject of allocation, see (Frischknecht 1998).

- Variant C: Waste flow value negative from building, value negative after processing but positive in road structure and
- Variant D: Waste flow value negative from building, value negative after processing and the road structure
- have a waste management function as a co-product ... "

The basic idea of such an allocation model is that 'the house' must benefit from the fact that there is a useful appliance of its waste (the designer of the house should be influenced by the LCA to use materials which can be re-used in other products or structures).

The 'estafette' allocation model (estafette = relay race) of (Seijdel 1994) and the ISO option of 'the number of subsequent uses' (ISO chapter 6.4.3) have the same intention: Taking the full burden away from the first product.

The main disadvantage of the allocation model of CML is that the value of the waste material is not known at the moment that the house is designed and built: Often more than 40 years before the moment of demolition! So, for the design and building stage of the house, the boundaries for allocation are not known, which is a rather unpractical situation.

There is also a methodological flaw in the CML system, caused by the fact that it is often the 'bundle of costs and benefits' and/or the governmental regulations, that influence the economic decisions. It is not the price of the waste materials as such which influences the economic decision.

In the example of the house, the reason for demolishing a house is often the fact that the market value of the ground area is more than the market value of the house. The EoL activities are then a co-product of another activity: Project development. The EoL activities are 'subsidised' then by the main product (being the creating of ground area). The market value of the waste hardly influences the economic decision in such cases. So there is no reason at all to give the market value of waste materials an important role in the allocation model.

3 The End of Life System of the EVR Model and a new order of preferences of EoL solutions ('Delft Order of Preferences')

In Chapter 1, it was concluded that EoL systems are complex, and the three paradigms (the cycle, the chain and the cascade) each cover only a part of the real practice.

In Chapter 2, it was concluded that the existing proposals for EoL allocation, based on the market value of recycled materials, don't fit reality. Therefore, a methodology has been developed, which:

- Reflects the underlying, causal, physical relationship (step 2 of ISO 14041) of the material flow in the recycling markets,
- can be regarded as an enhancement of early proposals in this field (Klöpffer 1996, Ekvall 1997, Kim 1997),
- keeps the environmental burden, the market value and the costs in the chain strictly separated, and
- deals not only with recycling, but also with enhancement of the lifetime of a product.

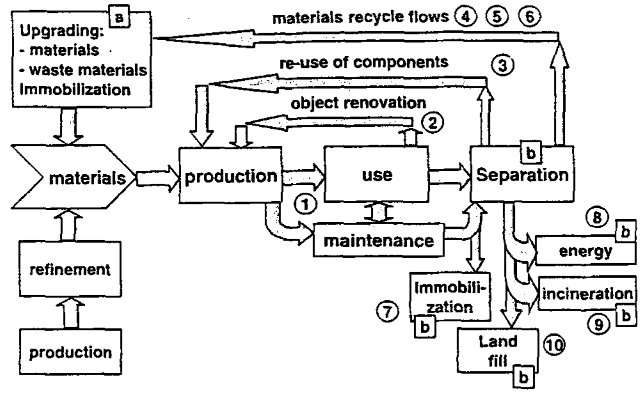

Fig. 5: The flow of materials in the Life Cycle

The way that the EVR model deals with End of Life and Recycling is depicted in Fig. 5, which depicts the major types of End of Life treatment and types of recycling. It is developed to describe and analyse the various kinds of complex modern life cycles of products, buildings, manufacturing plants, civil structures, etc.

The figures in Fig. 5 relate to the 'Delft Order of Preferences', a list of the 10 major systems for End of Life, used for structured and systemised analyses of (combinations of) design options:

1. Extending of the product life
2. Object renovation
3. Re-use of components
4. Re-use of materials
5. Useful application of waste materials (compost, granulated stone and concrete, slag, etc.)
6. Immobilization with useful application
7. Immobilization without useful application
8. Incineration with energy recovery
9. Incineration without energy recovery
10. Land Fill

It is important to realise that for big, modular objects (like buildings), there is not 'one system for End of Life', but there is always a combination of systems in reality.

The two basic rules for allocation in the EVR model are:

- Costs and eco-costs of all activities marked with 'b' are allocated to the End of Life stage of a product (transportation included).
- Costs and eco-costs of all activities in the block marked with 'a' are allocated to the material use of the new product (therefore, they are allocated to the beginning of the product chain).

There are many reasons to allocate the activities in the block marked with 'a' to the new product, and the activities in the blocks marked with 'b' to the old product. Three major arguments:

- Physical tracing of recycled material flows between the 'separation step' and the 'upgrading step' is often impossible (e.g. for recycled materials like metal scrap and waste paper there is a global trade with large stocks of several grades, so there is no direct physical relationship for those materials between the old product and the new product).

- The processes to upgrade or blend the different grades of recycled materials are often directly related to the new product, sometimes these processes are even integrated in the making of the new product (e.g. paper from recycled paper mills, steel from the Basic Oxygen Steelmaking process, etc.).
- For products with a long lifetime, other allocation models lead to wrong conclusions (Gielen 1999)[3].

In fact, the allocation of the activities of block 'a' to the new product is well in line with the allocation procedure in ISO 14041. The recycling activity has been split into subsystems type 'a' and type 'b' (step 1 in the procedure) and the subsystem type 'b' has been allocated to the old product while the subsystem type 'a' has been allocated to the new product. This is according to the physical relationship, in line with the ability to trace material flow in the recycling loop.

In line with the aforementioned allocation strategy, the 'bonus' to use recycled materials is taken at the beginning of the product chain, where the new product is created. Material depletion is caused here when 'virgin' materials are applied, material depletion is suppressed when recycled materials are applied.

The eco-costs of material depletion are defined by the costs of the fraction of 'virgin' materials, (1 – a), which are used for the new product. In formula (Vogtländer et al. 2001):

Eco-costs of material depletion
= (costs of 'virgin' materials) x (1 – a) (1)

where a is the fraction of used materials for the new product which stems from 'recycled' material (when upgrading is required, *after* the upgrading step), see also the Appendix and Note 11.

The 'separation' block in Fig. 5 comprises a chain of activities for most products. To end up with the best grade and the best purity of recycled materials, the separation step of products normally has to be organized in at least three steps:

1. Dismantling of the product in components,
2. demolishing the components (in a shredder),
3. separation of the output of the demolishing step (by a magnet, by eddy current, by air flow, etc.).

For buildings, the same principle applies: Dismantle the building first (taking out the wood, glass, cables, metals, etc.) prior to demolishing the building. The quality (purity) of recycled materials is then much better, compared with the 'classical method' (demolishing as the first step and separation afterwards).

This has two consequences for the future building industry:

- The design of a building has to be such that the building can easily be dismantled in order to be able to separate the several building materials ('design for recycling'), like 'design for recycling' as is common practice now for consumer electronics and cars;
- low capacity, transportable, processing equipment for 'separation' and crushing *at the site of the old building* is to be preferred instead of processing in big, centralized, separation plants, in order to avoid contamination and degradation of recycled materials during the material handling, transport and storage prior to processing.

4 The Eco-costs of End of Life and Recycling Activities

4.1 The eco-costs of End of Life of a product

All of the activities of Fig. 5 have their emissions, use of energy and use of additional materials (e.g. the equipment which is used), so all of these activities have eco-costs. As has been mentioned in the previous chapter, eco-costs of all activities (transportation included) marked with 'b' are allocated to the End of Life stage of the old product. In formula:

eco-costs of EoL = Σ (eco-costs of activity type 'b') (2)

Note that there is no 'estafette (relay race) effect' in the allocation model of the EVR model because of the clear division between activities 'b', to be allocated to the EoL of the old product, and activities 'a', to be allocated to the new product.

With regard to the summation of eco-costs according to equation 2, the analysis of two blocks of activities in Fig. 5 need extra attention:

- Incineration with energy recovery (block number 8),
- land fill (block number 10).

For incineration with energy recovery, there is a surplus of energy in the Life Cycle, which results in *negative* eco-costs of energy in equation 2, since energy is 'exported' to other products.

For 'Land Fill' it has been decided by the Dutch government that Land Fill is not a sustainable solution for waste treatment, and therefore has to be avoided (prevented)[4]. Consequently, the EVR model introduces the 'eco-costs of Land Fill, being the costs for the prevention of Land Fill.

The 'last' main prevention measures for Land Fill to reach the target (the 'marginal prevention costs') are:

- Making compost of bio waste: Processing costs of 80 Euro per 1000 kg,
- incineration of domestic waste in an environmentally acceptable manner: Processing costs of 100 Euro per 1000 kg,
- recycling building materials: Extra costs of separating materials at the EoL (partly 'dismantling' instead of total 'demolition' of the structure) is less then 100 Euro per 1000 kg in most cases.

Consequently, the 'eco-costs of Land Fill' have to be set at 100 Euro per 1000 kg, being the costs of these marginal prevention measures to reach the target.

It must be mentioned here that the target setting for Land Fill in The Netherlands has been a political choice: The Dutch

[3] Example: when the average lifetime of a car is 10 years, and when the production of cars has doubled in the past ten years, 45% recycled steel can be used in new cars when 90% of the steel of old cars is recycled. It is obvious that the fact that we need 65% virgin material for new cars is more relevant for our society in terms of material depletion and CO_2 emissions, than that we recycle 90% of the old cars.

[4] The governmental policy in The Netherlands is to restrict Land Fill. In 1996, 14% of the total waste flow was Land Fill, the target for 2010 is 4%! Land Fill for toxic materials is forbidden by law.

society is apparently 'willing to pay' about 100 Euro per 1000 kg in order to minimize Land Fill to the level of about 4% of the solid waste. In fact, the 4% target is the result of what is considered to be feasible in the technical/economical sense[5]. It is obvious that regions which are less densely populated will tend to take less expensive measures to prevent Land Fill (e.g. they will not be prepared to invest in incinerators and large-scale compost production). Or should these regions apply the 'best practices'? (see also the 'call for comments' in Vogtländer et al. 2000).

4.2 The eco-costs of using recycled materials for a product

Scrap metal, waste paper, waste glass, waste plastics, waste wood, etc. are regarded as the source for 'recycled' materials (as metal ore, pulp for paper, etc. is the source for 'virgin' materials). The eco-costs of the processes to make the new material from the waste material is allocated to the material which is used in the new product. In the EVR model, the eco-costs of materials of a new product are calculated according to equation 3:

$$\text{Eco-costs of materials} = \Sigma\,(\text{ eco-costs of energy} + \text{pollution prevention costs})_{\text{upgrading of recycled materials}} + \Sigma\,(\text{eco-costs of materials depletion} + \text{eco-costs of energy} + \text{pollution prevention costs})_{\text{virgin materials}} \qquad (3)$$

In most cases, virgin materials require more energy and cause more pollution than recycled materials (e.g. metals and glass). See also Table 1 in (Vogtländer et al. 2001)[6].

For situations of combined material production, such as in the Basic Oxygen Steelmaking process, equation 3 can be combined with equation 1 and written in the form of equation 4:

$$\text{Eco-costs of materials} = \Sigma\,(\text{costs of 'virgin' materials}) \times (1 - a) + \Sigma\,(\text{eco-costs of energy} + \text{pollution prevention costs})_{\text{processing of \underline{all} materials}} \qquad (4)$$

where a is the fraction of material for the new product which stems from 'recycled' material (*after* the processing step!).

4.3 The eco-costs of recycling

In the previous Chapters, 4.1 and 4.2, the way of calculation and allocating eco-costs of the recycling loop has been dealt with. This approach was focussed on the 'eco-costs of a product'.

In this chapter, we will deal with the subject of the 'eco-costs of recycling', and the ability to analyse ('closed loop') recycling systems as such.

[5] This situation is different from the setting of norms for emissions (Vogtländer et al. 2000). For emissions, the Dutch government has based their norms on the 'negligible risk level' for concentrations (in air and in water) and the corresponding 'fate analyses' (the link between concentration and emissions). Although there are many scientific disputes over these kind of calculations, they are less arbitrary than just the 'political will'.

[6] Note that in most of the LCA data on materials, the pollution data include pollution from the use of energy. In those cases, energy must not be counted extra in the equation for the total eco-costs, to avoid counting energy twice. See (Vogtländer et al. 2001).

To calculate the eco-costs of recycling the following activities are included, see Fig. 5:

- All activities type 'b', including the required transport and storage,
- all activities type 'a', including the required transport and storage.

For calculation (comparison) of recycling systems, the following assumptions are made:

- The recycling system is 'closed loop' (the materials of the EoL of a product are recycled and used for a new product of the same type),
- time (material hold-up) is not taken into account,
- when a material fraction α in the new product stems from recycling, a material fraction $(1 - \alpha)$ in the new product stems from 'virgin' material, and a fraction $(1 - \alpha)$ ends up in one of the following EoL systems (see the 'Delft Order of Preferences', Fig. 5, Chapter 3):
  - Immobilization without useful applications,
  - Incineration with energy recovery,
  - Incineration without energy recovery,
  - Land Fill.

Note that degradation of the product is taken into account by the 'bleeding' of a small fraction to either of the following EoL systems: Immobilization without useful appliances, Incineration, or Land Fill. This 'bleed' of material will lead to virgin material entering the life cycle loop and will keep the grade in the recycling loop at an acceptable level.

The 'eco-costs of a recycling system' are 'virtual', since the aforementioned assumptions hardly exist in real life (recycling systems are not 'closed loop' in the real sense of the word).

The total eco-costs of recycling are defined as (see Fig. 5 for activity type 'a' and type 'b'):

$$\text{Eco-costs of recycling} = \Sigma\,(\text{eco-costs of activity type 'b'}) + \Sigma\,(\text{eco-costs of activity type 'a'}) \qquad (5)$$

When a classical analysis is made of *recycling systems as such* (without integration with product chains), the benefits in terms of 'avoided eco-costs' might be taken into account. These benefits relate to the fact that fewer 'virgin' materials are used (resulting in less material depletion and normally less pollution and less use of energy at the material production stage).

When a is the fraction of material of the new product which stems from 'recycled' material, the 'net eco-benefit of recycling' can be defined for the total recycling system as:

$$\text{'Net eco-benefit of recycling'} = \Sigma\,\{(a + b + c) - (d + e) + f\} \times \alpha \qquad (6)$$

where:

a = (eco-costs of materials depletion)$_{\text{at 100\% virgin material}}$
b = (eco-costs of energy)$_{\text{at 100 \% virgin material}}$
c = (pol. prev. costs)$_{\text{at 100\% virgin material}}$
d = (eco-costs of energy)$_{\text{at 100\% recycled material}}$
e = (pol. prev. costs)$_{\text{at 100\% recycled material}}$
f = (eco-costs of immobilization, incineration or Land Fill)

The 'net eco-benefit of recycling' ranges from zero (α = 0, no recycling) to a maximum (α = 1, 100% recycling)[7], where α = 1 is not feasible because of the 'second law of thermodynamics'.

The purpose of equation 6 is to bring the positive effect of re-using materials within the boundary limits of the analysed recycling system. When 'total loops' or 'total systems' are to be analysed (when the product chains are included within the boundary limits), equation 6 must *not* be used, to avoid 'double counting' of the 'avoided eco-costs'.

5 The Value and the EVR of EoL and Recycling Systems

5.1 The market value in the recycling loop

The economics in the End of Life stage and the economics of recycling are rather complex, since, in most cases, products and materials in the End of Life stage have a negative market value (companies who take away discarded products are paid for it). People can earn money by keeping these products in stock, resulting in an enormous hold-up of discarded products world wide, and resulting in a certain pressure to get rid of it in an illegal way. Therefore, the 'free market of discarded products' has to be restricted in many ways by governmental regulations (e.g. prohibition of dumping certain materials and/or products in land fills), and the government has to force industry to recycle their products in a correct manner.

The services (activities) to recycle these products and materials in an environmentally correct manner have a positive added value. Within the framework of regulations and joint agreements between government and industry (the Dutch 'convenants'), a free market of recycling activities can thrive.

A special problem, however, for the free market of recycling is the fact that recycled materials fluctuate heavily in price. This instability of prices results from the fact that:

- Price speculation in recycled products is cheap (because of the negative investment in stock),
- some governments in the western economies subsidize processing of waste materials, while others do not (sudden introduction of subsidies, regulations and the like, disturb markets and market prices),
- some countries in the Far East buy waste materials (like waste paper) in enormous quantities at one time (transport of waste materials from Europe to the Far East is extremely cheap because of the surplus of empty containers returning to the Far East).

The aforementioned situation leads to the following consequences:

- The negative market value of discarded products and materials is indirectly determined by the governmental regulations and levies on waste treatment, which are a result of the 'willingness to pay' to avoid Land Fill,
- the market value of recycled materials (after upgrading) might be less than the total costs of recycling,

[7] A similar model is proposed for 'environmentally weighted recycling quotes', to replace the 'material recycling efficiency' used by several member states in the EU, which describes the performance of recycling systems (Huisman et al. 2000a) (Huisman et al. 2000b)

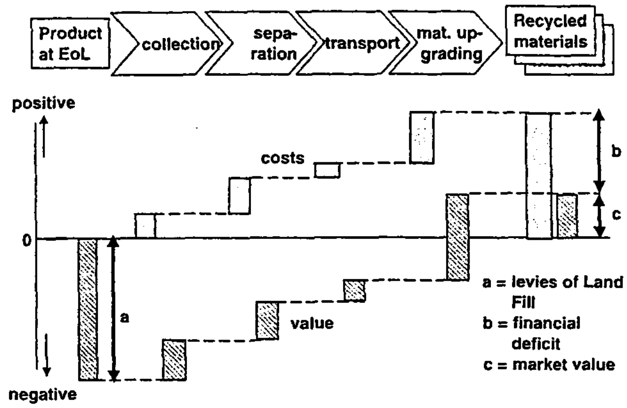

Fig. 6: The market value and the costs along the recycling chain for non-toxic consumer products

- the recycling activity is economically feasible when the added value of the recycling activity is more than the added costs.

The analyses of eco-costs, costs and the value of recycling chains must be done with great care. The best approach is to keep these 3 elements strictly separated along the chain, avoiding the total picture getting blurred by mixing up the economic and environmental aspects.

The market value and the costs along the recycling chain are depicted in **Fig. 6**.

The negative market value of a product when it is discarded ('a' in Fig. 6), is determined by the levy required for Land Fill. In the Netherlands this levy is set at 110 – 160 Euro by the Dutch government for non-toxic materials. It is the right governmental policy that this levy has been set slightly higher than the prevention costs – the eco-costs – of Land Fill (100 Euro per 1000 kg for non-toxic materials, see Chapter 4.1)[8]: In most cases, prevention is more attractive than Land Fill from the economic point of view.

Each step (activity) in the recycling chain adds value as well as costs.

At the end of the recycling chain, we expect a positive market value of the recycled materials ('c' in Fig. 6). The costs of recycling, however, are often higher than the market value of the recycled materials (this applies to most of the consumer products; waste paper is one of the exceptions). The deficit ('b' in Fig. 6) at the end of the recycling chain must be less than the levy 'a' at the beginning of recycling chain (otherwise there is no economic feasibility for recycling).

This deficit 'b' must be paid in one way or the other, to make the business of recycling profitable. There are 4 major forms of additional payments to the recycling chain:

1. The deficit of the recycling is compensated for by a 'waste treatment levy' ('verwijderingsbijdrage') which is paid by the consumer at the moment of purchase of the product; a list of levies for The Netherlands is given in **Table 1**.

[8] For toxic products Land Fill is forbidden in The Netherlands: Proper treatment of such waste is obligatory.

Table 1: The 'waste treatment levy' ('verwijderingsbijdrage') in The Netherlands

	Euro		Euro
Televisions	11.34	Electric garden tools	4.08
Portable radios, cassette players, etc.	1.13	VCRs	6.81
Fan	3.40	Domestic appliances	1.13
Washing machines	9.08	Electric tools	1.82
Electric music instruments	6.81	Freezers and refrigerators	18.15
Electric guitars	2.27	Audio appliances	2.27
Sewing machines	9.08	Grill, extractor fan, microwave	6.81
Central heating boilers	4.54	Car tyres	2.04

2. The deficit of the recycling is paid from other sources in the 'bundle of costs and benefits'. (An example is given in Chapter 2: The reason for demolishing a house is often the fact that the market value of the ground area is more than the market value of the house; the EoL activities are then a co-product of another activity: project development. See also the example in Chapter 6.)
3. The deficit is paid by the industry involved in the production and trade of the product type (e.g. glass bottles in The Netherlands).
4. Subsidies from governments.

5.2 The EVR model for more advanced sustainable EoL solutions

In the previous chapters, the EVR model has been described for waste treatment and recycling systems, systems 4 through 10 of the 'Delft Order of Preferences', see Fig. 5.

In this chapter, we will deal with:

1. Extension of the product life (choice of materials, construction type, maintenance systems, etc.).
2. Object renovation (e.g. refurbishing of buildings, renovation of buildings, using former building structures and/ or foundations).
3. Re-use of components (e.g. repair of cars with components from discarded cars).

The essence of these EoL systems is that the life of a product and/or the life of a product component is extended in time. In practice, all kinds of combinations of these 3 systems occur in complex products like office buildings, manufacturing plants, trucks, cars, etc. Therefore, the 'cascade' approach (see Chapter 1.2 and 3) is not suitable to tackle the problem of analysing these types of systems.

The way the extended life solutions are dealt with in the EVR model is similar to the approach which is used for eco-costs of depreciation of production facilities (Vogtländer et al. 2001), and is explained hereafter.

When, for example, the lifetime of a product is extended by 10%, the eco-costs per year are decreased by 10%. If this enhancement of the lifetime is achieved at the same costs and the same value per year, the EVR is decreased by 10%.

The underlying assumption is that eco-costs are distributed in a linear way over the lifetime of a product, similar to the depreciation of the costs of a product.

This underlying assumption is also used in **Table 2**, which provides an overview of the eco-costs of an office building, as

Table 2: Summary of the eco-costs of an office building (excluding energy during the use phase!), Example from (Vogtländer et al. 2001)

Summary description of an office building (typical)	**Eco-costs** (Euro/m^2)	**Lifetime** (years)	**Eco-costs** (Euro/m^2/annum)
Main materials for construction:			
– concrete, 300 kg/ m2 (eco-costs 0.2 Euro/kg, see Table 1)	60	40	1.5
– steel, 50 kg/m2 (eco-costs 1.80 Euro/kg, see Table 1 and 3)	90	40	2.25
– miscellaneous materials, 50 kg/m2 (glass, wood, PVC, etc.)	30	40	0.75
– building activity (energy, etc.)	40	40	1.00
Subtotal construction building structure	220	40	5.50
Building systems (elevators, heating, electrical, water, etc.)	60	20	3.00
Interior (painting, decorating, furniture, etc.)	120	15	8.00
Computer system (one screen per employee at 33 m2)	9	3	3.00
Maintenance of building and building systems per year	3	–	3.00
End of Life:			
Demolition + transport of materials at End of Life	20	40	0.50
Disposal of construction waste (eco-costs 0.10 Euro/kg)	40	40	1.00
Subtotal End of Life	60		1.50
Total			**24**

given in (Vogtländer et al. 2001). In this table, the lifetime of the elements of an office building is used to calculate the eco-costs per m² per annum for each element, in order to determine the eco-costs per m² per annum of the total. Note that the subsystems in Table 2 (building structure, building systems, interior, computer systems) each have different lifetimes.

It is advised to approach the analyses of extended life solutions (with several subsystems) by calculating the 'eco-costs per annum', applying the following equations:

$$(\text{Eco-costs per annum})_{subsystem} = (\text{eco-costs / lifetime})_{subsystem} \quad (7)$$

and

$$(\text{Depreciation per annum})_{subsystem} = (\text{value / lifetime})_{subsystem} \quad (8)$$

Combining (7) and (8) results in:

$$(\text{Eco-costs per annum})_{subsystem} = (\text{depreciation per annum})_{subsystem} \times EVR_{subsystem} \quad (9)$$

For the total extended life system:

$$(\text{Eco-costs per annum}) = \Sigma \{ (\text{depreciation per annum})_{subsystem} \times EVR_{subsystem} \} \quad (10)$$

The meaning of equation 10 is that the eco-costs per annum can be derived from the normal costs of depreciation by multiplying it with the EVR of that subsystem. An example of such a type of calculation is given in Table 3, for the same office building as given in Table 2.

One may argue that equation [10] may also be used in situations where the depreciation is not linear, but follows the real market value of a subsystem.

6 Example: A warehouse building

As an example of the EoL and recycling in the EVR model, the concrete floor slab and the steel superstructure (including roof, cladding and warehouse racks) have been analysed for EoL and recycling solutions. The summary of this analysis is given in Table 4.

Table 3: Summary of the eco-costs of an office building (excluding energy during the use phase!). This office building is the same as the office building in the example of Table 2

Summary description of an office building (typical)	**Investment** (Euro/m²)	**Lifetime** (years)	**Depreciation** (Euro per m² per year)	**EVR**	**Eco-costs** (Euro per m² per year)
Subtotal construction building structure	630	40	15.75	0.35	5.50
Building systems (elevators, heating, electrical, etc.)	170	20	8.50	0.35	3.00
Interior (painting, decorating, furniture, etc.)	340	15	22.70	0.35	8.00
Computer system (one screen per employee at 33 m2)	30	3	10	0.30	3.00
Maintenance of building and building systems per year		–	15	0.20	3.00
End of Life:					
Demolition + transport of materials at End of Life	40	40	1	0.50	0.50
Disposal of construction waste (eco-costs 0.10 Euro/kg)	40	40	1	1.00	1.00
Subtotal End of Life					1.50
Total					**24**

Table 4: The eco-benefit (in Euro) of recycling of the steel of the steel structure and re-use of the floor slab of a warehouse. Simplified example of a warehouse of 900 m², 10 m high, 920 pallets, floor slab 551,200 kg reinforced concrete, steel structure 51,000 kg, steel sheets for roof and cladding 22,000 kg. For details see also (Vogtländer et al. 2001)

Note: All values in Euro	**0% recycled**	**95% recycled or re-use**	**Eco-benefit**
EoL of Old Building			
Eco-costs of Land Fill	62,400	3,100	59,300
Eco-costs of transport	600	600	0
Total eco-costs EoL	63,000	3,700	
		Total eco-benefit EoL	59,300
Materials for new building			
Eco-costs of steel	84,500	31,800	52,700
Eco-costs of concrete floor	99,500	5,000	94,500
Total eco-costs materials	184,000	36,800	
		Total net eco-benefit materials	147,200
All values in Euro		**Total net eco-benefit**	**206,500**

The warehouse is the same warehouse as given in (Vogtländer et al. 2001), and can be summarized with the following characteristics:

- Function: 920 pallet places (900 m^2, outside height 10 m),
- concrete floor slab: 551,200 kg, eco-costs 99,459 Euro,
- steel, total: 73,000 kg, eco-costs 84,568 Euro,
- total eco-costs of the warehouse, excluding EoL: 257,481 Euro.

The maximum eco-costs of EoL, e_0, have been calculated under the assumption that all materials are dumped in a Land Fill.

The minimum eco-costs of EoL, e_{95},have been calculated for 95% recycling, so only 5% of the total weight ends up in Land Fill.

The maximum net eco-benefit of recycling, allocated to the 'old building' equals: $e_0 - e_{95}$.

The 'avoided eco-costs of materials' in this case totally depend on:

- The function of the new building which will replace the old building, and
- the decision of the architect on the possibilities to re-use parts of the old floor slab and to apply recycled materials.

Hence the 'avoided eco-costs of materials', being the net eco-benefit of materials, are allocated to the new building.

Suppose the new building has exactly the same function (a warehouse) and the architect applies recycled steel for 95% of the steel elements, and uses the old floor slab.

For this case, the following data has been calculated, and provided in Table 4:

- The eco-costs without recycling and re-use,
- the eco-costs of 95% recycling and re-use,
- the net eco-benefit of materials.

Note that, when the design load on the floor slab of the new building is less, the thickness of the floor slab can be less, consequently with a lower amount of concrete required and therefore less net benefits of eco-costs.

In the case that the floor slab has to be demolished and removed, the market value and the costs along the recycling chain can be analysed, see Fig. 6.

Suppose:

- The negative market value (the levy) of Land Fill is 110 Euro,
- the costs of crushing and grinding of the floor slab (including extra transport) is 90 Euro,
- the market value of the granulated material is 10 Euro.

In this case, recycling is economically feasible, since the recycling operation results in an added value of 120 Euro at added costs of 90 Euro. In Fig. 6 the size of 'b' is less than 'a'.

The fact that the market value of granulate is less than the costs of the granulate is not ruling the economic decision: This deficit is paid from other sources in the 'bundle of costs and benefits' of the total project.

However, when the size of 'b' is more than the size of 'a', the recycling operation as such has less added value than added costs, and will therefore not happen in a free market economy. When society insists on recycling in such cases, governmental regulations, levy systems or subsidies are required to make recycling happen.

7 Discussion

Although the methodology for recycling and EoL has been developed within the framework of the EVR model, the same methodology can be used in other systems, like the eco-indicator 95 and 99. This is because of the fact that eco-costs, costs and value are strictly separated from each other. Computer models which are used in the design stage of products, like Simapro and Ecoscan, are structured according to similar principles, which is in line with data sets of BUWAL (providing LCA data on virgin metals as well as 'secondary metals').

Confusion on the analyses of recycling systems stem from the fact that different parameters in the system are often mixed up:

a) Eco-costs of recycling activities(Equation [5]),
b) eco-benefit of recycling (Equation [6]),
c) costs of recycling activities,
d) market value of recycling activities,
e) market value of the recycled materials.

Note that the EVR (ecocosts/value ratio) calculations, as described in (Vogtländer et al. 2001), are only allowed for the parameter a), c) and d) of the aforementioned list, and not for parameter b) nor e).

With regard to the enhancement of the durability of products (equation [10]), it is important to realise that the lifetime of *all* subsystems of a product must preferably be the same, when it is not possible to split the product into subsystems at the End of Life. Subsystems with a longer lifetime than the other subsystems suffer from a 'waste of quality'.

However, one must realise that the End of Life of a product is not a matter of the technical lifetime only, it is also related to value aspects of the product. A product can become obsolete for the user for many reasons (van Nes et al. 1998):

1. Technical: The product is worn out and no longer functioning properly,
2. economic: New products have a lower level of 'Costs of Ownership' (maintenance, energy, etc.),
3. ecological: New products have less harmful impact in the use phase (maintenance, energy, etc.)
4. esthetical: New products have a nicer look, a more fashionable design, a better image ('feel good factor')
5. functional: New products fulfil more functions or fulfil functions better
6. psychological: Old products have a negative emotional factor (unpleasant history), new products have a positive emotional factor (gift, pleasant history), 'feel good factor'.

To cope with the obsolescence of point 2 through 5, the product design must be modular. An obsolete module can then be easily replaced by a new one, instead of replacing the whole product. This principle applies also to the design of buildings.

The fact that a product (or its subsystem) can become obsolete before the product is worn out and no longer functioning properly, is the reason that one should take the 'economic lifetime' as lifetime in the LCA calculations (equation 7), instead of the 'technical lifetime'.

This is the reason why the depreciation of the eco-costs in the EVR model is done in parallel with the economic depreciation (equations 7-9).

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8 Appendix: The Virtual Eco-costs and the EVR model

The basic idea of the EVR (Eco-costs/Value Ratio) model is to link the 'value chain' (Porter 1985) to the ecological 'product chain'. In the value chain, the added value (in terms of money) and the added costs are determined for each step of the product 'from cradle to grave'. Similarly, the ecological impact of each step in the product chain is expressed in terms of money, the so called eco-costs. See **Fig. 7**.

The eco-costs are 'virtual' costs: These costs are related to measures which have to be taken to make (and recycle) a product "in line with earth's estimated carrying capacity"[9].

[9] In 1995, the World Business Council for Sustainable Development (www.wbcsd.ch/eurint/eeei.htm) described the role for industry in their definition of eco-efficiency as: "The delivery of competitively priced goods and services that satisfy human needs and bring quality of life while progressively reducing ecological impacts and resource intensity, through the life cycle, to a level at least in line with earth's carrying capacity."

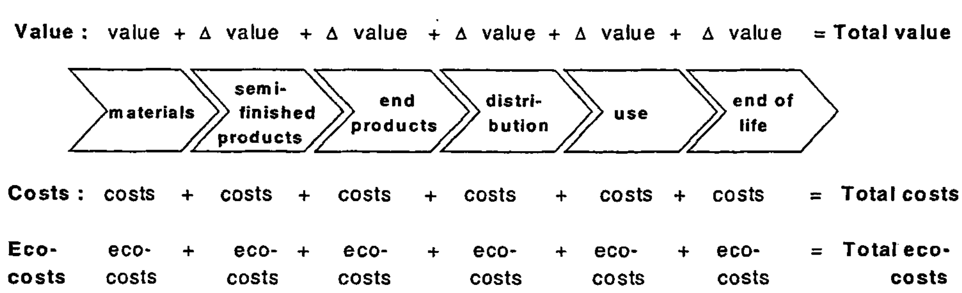

Fig. 7: The basic idea of combining the economic and ecological chain: 'the EVR chain'

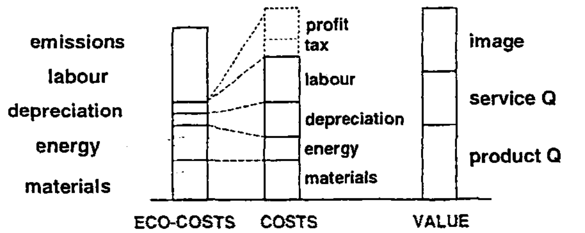

Fig. 8: The decomposition of 'virtual eco-costs', costs and value of a product

These costs have been estimated on the basis of technical measures to *prevent* pollution and resource (materials + energy) depletion to a level which is sufficient to make our society sustainable.

Since our society is yet far from sustainable, the eco-costs are 'virtual': They have been estimated on a 'what if' basis. They are not yet fully integrated in the current costs of the product chain (the current Life Cycle Costs). The ratio of eco-cost and value, the so called Eco-costs / Value Ratio, EVR, is defined in each step of the chain as:

$$\text{EVR} = \text{eco-costs / value} \qquad (6)$$

For one step in the production+distribution chain, the eco-costs, the costs and the value[10] are depicted in Fig. 8.

The five components of the eco-costs have been defined as 3 'direct' components plus 2 'indirect' components:

- Virtual pollution prevention costs, being the costs required to reduce the *emissions* of the production processes to a sustainable level (Vogtländer et al. 2000),
- eco-costs of *energy*, being the price for renewable energy sources,
- *materials* depletion costs, being (costs of raw materials) x (1-a), where a is the recycled fraction[11],
- eco-costs of *depreciation*, being the eco-costs related to the use of equipment, buildings, etc.,
- eco-costs of *labour*, being the eco-costs related to labour, such as commuting and the use of the office (building, heating, lighting, electricity for computers, paper, office products, etc.).

Based on a detailed cost-structure of the product, the eco-costs can be calculated by multiplying each cost element with its specific Eco-costs / Value Ratio, the EVR. These specific EVRs have been calculated on the bases of LCAs. Tables are provided in (Vogtländer et al. 2001).

The pollution prevention costs can be calculated in four steps:

1. LCA calculation according to the current standards (ISO 14041),
2. Classification of the emissions in 7 classes of pollution,
3. Characterization according to characterization multipliers as used in e.g. the Eco-indicator '95, resulting in 'equivalent kilograms' per class of pollution,
4. Multiplication of the data of step 3 with the 'prevention costs at the norm', being the marginal costs per kilogram of bringing back the pollution to a level 'in line with earth's carrying capacity'.

The following 'prevention costs at the norm' are proposed for The Netherlands and Europe:

- Prevention of acidification: 6.40 Euro/kg (SOx equivalent)
- Prevention of eutrophication: 3.05 Euro/kg (phosphate equivalent)
- Prevention of heavy metals: 680 Euro/kg (calculation based on Zn)
- Prevention of carciogenics: 12.30 Euro/kg (PAH equivalent)
- Prevention of summer smog: 50.00 Euro/kg (calculation based on VOC equivalent)
- Prevention of winter smog: 12.30 Euro/kg (calculation based on fine dust)
- Prevention of global warming: 0.114 Euro/kg (CO_2 equivalent)

These 'prevention costs at the norm' are based on the so called 'marginal prevention costs' of emissions. The way these marginal prevention costs are determined is depicted in Fig. 9. For each type of emission, the costs and the effects (in terms of less emissions) are accumulated for several prevention measures to be taken (a 'what if' calculation). At a certain point of the curve, the 'norm for sustainability' is reached. The marginal prevention costs are defined by the costs per kg reduction of the 'last' measure, depicted as line b.

The 'norms for sustainability' are based on the 'negligible risk levels' for concentrations (in air and in water) and the corresponding 'fate analyses' (the link between concentration and emissions).

For details on these prevention costs, see (Vogtländer et al. 2000).

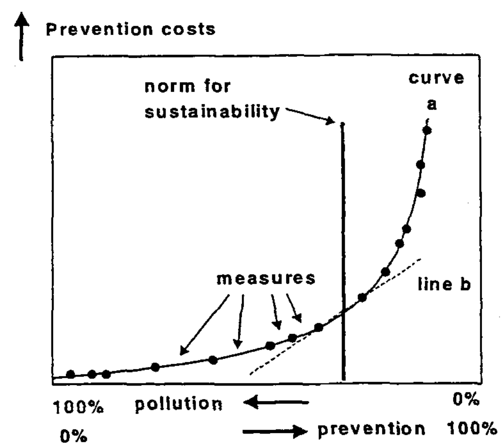

Fig. 9: The way the marginal prevention costs are calculated from emission prevention measures for a certain region

[10] Within the business chain, the value equals the market price. From the consumers point of view, the value equals the 'fair price' (Gale 1994). Note: il the business chain, the cost for the buyer is the value for the seller.

[11] In theory, one must apply the 'present market value' (discounted) of the 'sustainable alternative in the future' for the material which is depleted here according to the model of Hotelling (Pearce et al. 1990, Henley et al. 1997). For most of the materials, however, there is no reason to believe that this 'present discounted market value of the sustainable future alternative' deviates much from the current average material prices (examples: tin, copper, iron), since the functionality of these materials can be replaced by alternatives which are not more expensive for their specific functions. So the present price levels can be applied for 'costs of raw materials' in this equation.
An exception is oil as a source for plastics. In the EVR model, the costs for ethanol from biomass has been taken for the 'costs of raw materials' for plastics.